MULTI - OBJECTIVE OPTIMIZATION OF ELECTRO - DISCHARGE MACHINING (EDM) PROCESS

by

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CERTIFICATE

This is to certify that the work entitled, "MULTI-OBJECTIVE OPTIMIZATION OF ELECTRO-DISCHARGE MACHINING (EDM) PROCESS" by V. Srinivasa Anand has been carried out under our supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

Optimization in manufacturing processes has attracted considerable attention. However, it is still desirable to develop new models to meet the needs for unique machining processes, especially where the practical considerations force us to optimize several objectives simultaneously.

Making of holes by Electro Discharge Drilling is not uncommon. However, not much information is available about the effect of ontime, depth of penetration and tool diameter on the technological characteristics during electro discharge drilling operation. Hence, an attempt is made in this work to formulate a new multi-objective optimization problem for the EDM process and solve the resulting model for optimality.

The EDM data obtained from the experimental investigations of other researchers are analyzed by means of regression methods and a mathematical model of the process is established. This model shows the relationship between the input parameters which have to be set on the machine and the output parameters which describe the effectiveness of the process. This mathematical model is then solved using Non-Linear Goal Programming technique. The optimization problem is essentially finding the value of the input parameters which satisfy some technological constraints and gives the "best" solution considering the following optimizing criteria : Material Removal Rate, overcut, surface roughness, Relative Electrode Wear, Tool Wear Rate and taper.

CHAPTER 1

INTRODUCTION

1.1 Introduction

There has been a rapid growth in the development of harder and difficult-to-machine metals and alloys during the last two decades. Conventional edged tool machining is uneconomical for such materials and the degree of surface finish and accuracy attainable are also poor. The newer machining processes developed to process such materials are called 'Modern Machining Processes' or 'Unconventional Machining Processes' . As a group they are characterized by an insensitivity to the hardness of the workpiece material; hence, they are suitable for shaping parts from fully heat-treated materials, avoiding the problems of distortion and dimensional change that often accompany heat-treatment. These modern machining methods are classified according to the type of fundamental machining energy employed, namely, mechanical, electrochemical, chemical or thermoelectric [17].

In thermoelectric electric processes, thermal energy is employed to melt and vaporize tiny bits of workpiece material by concentrating the heat energy on a small area of workpiece. These methods include Electro Discharge Machining (EDM), Laser Beam Machining (LBM), Plasma Arc Machining (PAM) and Ion Beam Machining (IBM), to name a few.

1.2 Electro Discharge Machining

Electro Discharge Machining (EDM), sometimes referred to as 'spark machining', is a method of removing metal by a series of rapidly recurring electrical discharges between an electrode (the cutting tool) and the workpiece in the presence of a liquid (usually hydrocarbon dielectric). Minute particles of metal or "chips" are removed by melting and vaporization, and are flushed from the gap between the tool and the workpiece. The workpiece which constitutes one of the electrodes between which the sparks occur, must be made of electrically conductive material. The other electrode (tool), which also must be made of electrically conductive material, is located in close proximity to but not in contact with the workpiece during cutting.

An EDM machine is needed to hold and locate the tool in a proper mechanical relationship with respect to the workpiece. It incorporates a means for relative motion between the tool and the workpiece to maintain the desired gap, which is the space between the tool and the workpiece. Modern machines provide for automatic maintenance of the preselected gap by some form of servo control, which acts as a power feed.

EDM usually requires the presence of a liquid in the arc gap. The principal functions of this liquid are, to provide a path for the discharge of electrical currents, to remove the metal particles produced from the gap and to cool the tool and the workpiece. These functions are most easily achieved by forcing the liquid through the gap, thus requiring a pump. EDM is generally done with the gap well submerged in a dielectric tank. A spark generating apparatus is connected to the tool and the

1.3 Need and Objective of the Work

1.3.1 Need

The multi-criteria optimization problem is one of the most frequently encountered practical problems. As far as metal cutting is concerned, the problem mostly manifests in the following manner : it is required that an individual operation be done at a high level of efficiency but no single objective can be identified as being of paramount importance. In such cases one may have no recourse but to optimize with respect to several criteria. Goal programming provides a solution which tends to compromise between the various conflicting objectives.

In recent years, several efforts have been made to deal with the optimization of manufacturing processes. (A review of work in the optimization of EDM process will be presented in Chapter 2). It is still desirable to develop new models to meet the needs for unique machining processes, especially where the practical considerations force us to optimize several objectives simultaneously.

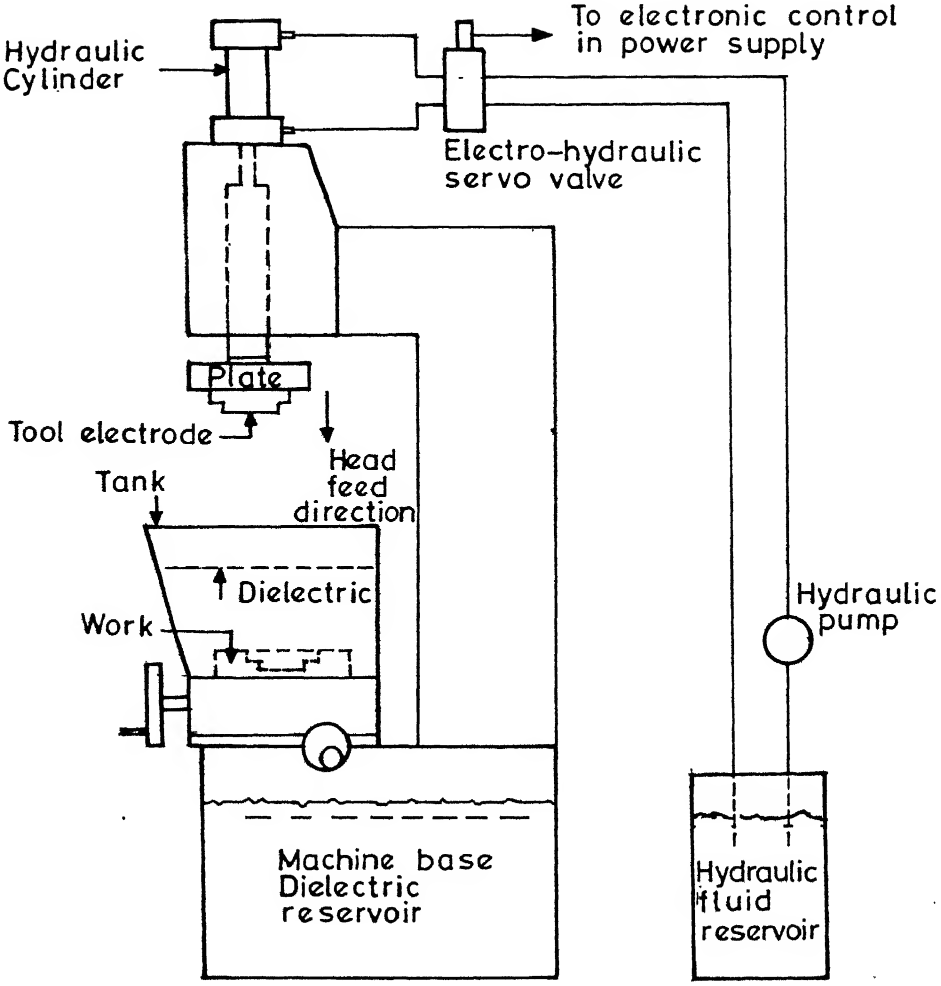

Fig. 1·1 BASIC COMPONENTS OF AN ELECTRICAL DISCHARGE MACHINE

Making holes by Electro Discharge Drilling is not uncommon. However, not much information is available about the effect of ontime , tool diameter and the depth of penetration on the technological characteristics during electro discharge drilling operation. Hence, an attempt is made in this work to formulate a new multi-objective optimization model for the EDM process and solve the resulting mathematical model for optimality.

1.3.2 Objective

The objective of this thesis is to develop a multi-objective optimization model for Electro Discharge Machining where the measures of performances like Material Removal Rate, Surface Roughness, etc., are a function of the tool diameter, depth of penetration and ontime. Based on a set of pre-specified goal values for these measures, the optimal values for the parameters are to be determined. Here "optimum" is defined as "goal efficient" i.e., the aspiration levels on each of the objectives are to be realized if "optimality" is to be present. The technique of Non-Linear Goal Programming (NLGP) is used to solve the optimization problem.

1.4 Organization of the Thesis

Previous works on optimization of EDM process are discussed in chapter 2. Chapter 3 describes the Non-Linear Goal Programming algorithm. The modeling techniques used in building a mathematical model of the process are also described in chapter 3. In chapter 4, the computer implementation of the solution methodology used is discussed. The results of the test problems are presented in Chapter 5. The results obtained by applying compared with their results. This chapter also includes the the results of the analysis to evaluate the impacts of rotating the preference in objectives and fixing one variable at a time . Chapter 6 sums up the conclusions drawn from the present study and offers certain suggestions for further study.

CHAPTER 2

LITERATURE REVIEW

This chapter is devoted to a survey of the existing literature on the optimization of EDM process. A review of the trends in the optimization from single objective optimization to multi-objective optimization is presented . A brief review on some parametric studies in EDM is also included.

2.1 Introduction

EDM was originally developed by Lazarenko and Lazarenko in U.S.S.R. in the year 1943. Advancements also took place simultaneously in Europe and U.S.A. Since then research is going on in different areas of the process and EDM is gaining wide application and popularity.

Two types of EDM machines are commercially available in the market, namely the pulse generator type and the relaxation circuit based. Due to inherent process capability, the later is used for roughing operations where bulk removal of material is considered [11].

2.2 Parametric Studies in EDM

Snoeys, Cornelissen, and Leuven [22] investigated the effect of theoretical discharge duration, average current and average working voltage on work piece material removal rate, electrode material removal rate, number of effective discharges per second, number of arcs per second and the sum of discharge durations per second. They obtained a set of curves showing the variation of each of these items versus the investigated of effective discharges and the material removal rate. Also, the statistical distribution of the effective discharge time as a function of working parameters was established.

Kahng and Rajurkar [9] in their paper dealt with the surface characteristics behavior of EDM eroded surface. They reported that increment in pulse duration - one of the many influencing parameters - not only increases surface roughness but also results in the increase in depth of heat affected zone.

Singh, Miller and Urquahart [20] made a comprehensive study of the influence of various EDM parameters such as gap voltage, gap current, dielectric fluid pressure, electrode material and impulse frequency on machining characteristics such as Material Removal Rate (MRR), dimensional accuracy, and surface finish. A simple relationship evolved from these experiments showed that low voltages exhibit high MRR with poor surface finish while high gap voltage gave lower MRR, fine surface finish and good dimensional accuracy.

Indurkhya's experimental study [8] reported the effect of ontime, depth of penetration, and tool diameter on the technological characteristics during Electro Discharge Drilling. Using these experimental responses a response surface model was evolved. Appendix - A describes the procedure in detail.

2.3 Optimization of EDM Process

2.3.1 Single Objective Optimization:

A survey of literature on the optimization of EDM process reveals that two types of approaches are being used; estimation of the relationship of responses to process variables and optimizing these under the process constraints on one hand, and estimation of the inter-relationship of such responses without going into their relationship with process variables, on the other hand.

Initially, all work on EDM optimization was confined to optimizing the various objective functions separately. Pal, Mishra and Bhattacharya [16] carried out experiments on Electro Discharge Machine based on R-C circuit and estimated the relationships of MRR and Electrode Wear Rate (EWR) to process variables like capacitance and resistance and optimized these separately under the process constraints.

Mukherjee and Pal [11] derived an expression for contribution rate as a function of process variables (pulse width and frequency) so that an indicator to measure the economic objectives of the process is obtained. They used Complementary Geometric Programming algorithm to optimize the contribution rate under technical and technological constraints. The other objective functions like MRR, EWR etc., were optimized using Linear Programming. Later, they reported similar work on Relaxation type Electro Discharge Machining process [12].

Beigel [2] looked at energy consumption in the EDM process and evaluated that information in terms of maximizing material removal rate per unit of power consumed. He also presented an approach for determining the parameters of the EDM process so that energy consumption can be optimized.

Cornelissen, Snoeys, and Kruth [4] utilized the surface response technique to find out the inter-relationship among MRR, EWR and Surface Roughness (SR) without going into their relationship with process variables.

2.3.2 Multi Objective Optimization:

However, it is well known that the most ideal situation for a decision maker would be such when he is able to tackle multiple objectives simultaneously.

Mukherjee and Pal [13] first reported the application of Linear Multi Objective Programming methods in optimizing the operation of relaxation circuit based EDM process . The process variables were Resistance and Capacitance and the objective functions considered were MRR, EWR and Specific Material Removal Rate i.e., the ratio of MRR to EWR. Their paper utilized an interactive programming based algorithm [28] and the solution set finally offered to the decision maker consisted of a set of discrete solutions, each of which were associated with a particular set of responses of the decision maker to the trade offs associated with each variable.

Osyczka,et al [15] in their paper established an investigation procedure of the EDM process on the basis of experiments. The data obtained from these experiments were analyzed to produce a mathematical model of the process. In this model the decision variables were input quantities like discharge current, pulse duration, and pulse interval time and the output quantities were objective functions like MRR, Tool Electrode Wear, power consumed etc. This model was solved using Min - Max approach to multi-criteria problems [14]. Their approach was that the phenomenological model of the process constitutes the basis of its analysis and optimization. Their work was carried out on a pulse generator type EDM machine.

2.4 Scope of Present Work :

From the above review it is evident that not much information is available about the effect of ontime , tool diameter and the depth of penetration on the technological characteristics during electro discharge drilling operation. Hence, an attempt is made to formulate a new multi-objective optimization model for the EDM process based on Indurkhya's experimental work considering the following functions - Material Removal Rate , Surface Roughness, Relative Electrode Wear , Overcut , Taper and Tool Wear Rate . The final mathematical model is solved using Non-Linear Goal Programming (NLGP) algorithm. The optimum values of the design variables are determined by satisfying the bounds on the different variables as the constraints.

A computer program based on the above approach makes it ssible to determine the optimum machining conditions for erent objectives and different constraints, depending on the

CHAPTER 3

MATHEMATICAL MODELING AND SOLUTION METHODOLOGY

In this chapter, the focus will be on development of a nonlinear goal programming model for EDM. This chapter also addresses the technique of goal programming.

As we have seen in the last chapter, many research papers have appeared covering various aspects of EDM process parameters and their effect on machining performance. In this chapter, we attempt to structure the problem of finding the optimal parameters for EDM as a Non-Linear Goal Programming Model.

3.1 Mathematical Modeling

In this section, we derive the relationships for the dependent variables like Material Removal Rate, Overcut, etc., in terms of the independent variables. Also, the optimization of EDM process is formulated as a multi-criteria problem.

3.1.1 Expressions For the Dependent Variables

Indurkhya [8] studied Electro Discharge Drilling operation and evolved mathematical models for Material Removal Rate (MRR), Overcut (OC), Surface Roughness (SR), Relative Electrode Wear (REW), Tool Wear Rate (TWR) and Taper (TPR). The details of Indurkhya's study are presented in Appendix A. It is observed that in all his models the dependent variables are expressed as function of the coded levels of the factors (independent variables) instead of the actual values of the factors. For the present study ,all these models had to be as function of the actual values of the independent variables.

Using the models developed by Indurkhya, 125 data sets have been generated (with five levels for each factor) so as to fit a new model where the dependent variables are a function of the actual values of the independent variables. The model which gave the best value of R^2 achieved by the least squares has been selected in each case. Two models were found to be suitable for the objective functions. Table 3.1 gives the regression characteristics.

Model 1:

$$Y = B0\ X1^{B1}\ X2^{B2}\ X3^{B3}\ e^{B4X3}$$

or

$$\mathrm{Ln}\ Y = B0 + B1\ \mathrm{Ln}(X1) + B2\ \mathrm{Ln}(X2) + B3\ \mathrm{Ln}(X3) + B4\ X\cancel{4}3$$

Model 2:

$$Y = B0 + B1/X1 + B2/X2 + B3/X3$$

Based on the above approach, the following relationships are estimated :

$$MRR = 34.5359\ D^{0.410}\ d^{-0.014}\ t^{0.435}\ e^{0.007t}$$

$$OC = 0.0159\ D^{0.524}\ d^{-0.031}\ t^{0.020}\ e^{0.002t}$$

$$SR = 1.15027\ D^{-0.088}\ d^{0.031}\ t^{0.283}\ e^{0.001t}$$

$$REW = 4225.95\ D^{-0.901}\ d^{-0.014}\ t^{-1.099}\ e^{0.007t}$$

Table 3.1 : Regression Analysis Characteristics :

Response	R - Squared	F - Statistic			Coefficients		
(Model no.)		(with 4 & 120 dof)	B0	B1	B2	B3	B4
MRR (model 1)	0.8116	129.2552	3.542	0.410	-0.014	-0.483	0.007
Overcut (model 1)	0.9466	532.0408	-4.136	0.524	-0.031	0.020	0.002
REW (model 1)	0.9520	594.3839	8.349	0.900	-0.014	-1.099	0.007
TWR (modle 1)	0.8881	238.0175	6.464	-0.085	-0.164	-1.499	0.014
ROUGH (model 1)	0.9189	339.7382	0.140	-0.088	0.031	0.283	-0.001
TAPER (model 2)	0.8035	160.8484	-0.124	1.539	7.441	7.502	*

$$TWR = 641.62\ D^{-0.085}\ d^{-0.164}\ t^{-1.499}\ e^{0.014t}$$

$$TPR = -0.124 + 1.539/D + 7.441/d + 7.502/t$$

3.1.2 Problem Formulation

Mathematical description of the EDM process obtained from above allows us to build an optimization model of this process. In this model, the decision variables are the input quantities viz.,

D, diameter of the tool , mm

d, depth of penetration , mm

and t, ontime , us

The output quantities like MRR, OC, etc., which are expressed in terms of the above decision variables, form the objective functions. The optimization model in which several objectives can be considered has the greatest practical significance. This leads us to a multi-criteria optimization model where the objective functions are as follows :

1) Material Removal Rate

Material Removal Rate (MRR) is one of the most important machining characteristics in any metal cutting process; more so in EDM. MRR is directly linked to the productivity and hence is to be maximized. The expression for MRR (expressed in mg/min.) is follows :

$$MRR = 34.5359\ D^{0.410}\ d^{-0.014}\ t^{0.435}\ e^{0.007t} \qquad (3.1)$$

2) Overcut

Because of the side sparks, overcuts are found to occur be minimized and the expression for OC (in mm) is as follows :

$$OC = 0.0159\ D^{0.524}\ d^{-0.031}\ t^{0.020}\ e^{0.002t} \qquad (3.2)$$

3) Surface Roughness

The surface produced by EDM consists of microscopic craters. When the energy content per pulse is high, the depth of craters will increase causing a poorer surface finish. Surface Roughness (SR) is to be minimized. The expression for the surface finish (in microns) in terms of the parameters is given below.

$$SR = 1.15027\ D^{-0.088}\ d^{0.031}\ t^{0.283}\ e^{0.001t} \qquad (3.3)$$

4) Relative Electrode Wear

Relative Electrode Wear (REW) is defined as follows - it is the ratio of the volume of the metal removed from the tool electrode to the volume of metal removed from the work piece. It is to be minimized and is given by the following expression :

$$REW = 4225.95\ D^{-0.901}\ d^{-0.014}\ t^{-1.099}\ e^{0.007t} \qquad (3.4)$$

5) Tool Wear Rate

Tool Wear Rate (TWR) is directly related to the cost of EDM tooling. Hence, it is to be minimized. The expression for the TWR (in mg/min) is as follows :

$$TWR = 641.62\ D^{-0.085}\ d^{-0.164}\ t^{-1.499}\ e^{0.014t} \qquad (3.5)$$

6) Taper

In EDM process, tapering effect will be produced due to the presence of a frontal spark accompanied by side spark in the midst of suspended particles. Taper (TPR) is to be minimized. The

$$TPR = -0.124 + 1.539/D + 7.441/d + 7.502/t \qquad (3.6)$$

Furthermore, the model will contain the feasible ranges for the decision variables as the constraints to define a bounded design region.

3.2 Solution Methodology

In this section, the technique of goal programming is discussed. In the second part, the final NLGP model for the EDM process is developed.

3.2.1 Goal Programming

3.2.1.1 Introduction

Initially conceived as an application of single objective programming by Charnes and Cooper, Goal Programming (GP) gained popularity in 1960's and 1970's. GP is now an important area of multi-criteria optimization [23,25,27].

In a typical real world situation, goals set by the decision maker are achievable only at the expense of other goals. Furthermore, these goals are incompatible. Thus, there is a need to establish a hierarchy of importance among these incompatible goals so that the most important goals are satisfied or have reached the point beyond which no further improvements are possible. If the decision maker can provide an ordinal ranking of goals in terms of their contribution or importance to the organization, the problem can be solved using Goal Programming.

The Linear Goal Programming technique based on the two phase simplex algorithm had been used for solving multiple objective functions and/or the coupling constraints in metal cutting being nonlinear, they have to be approximated to linear models before applying LGP techniques. In such a situation, it is more realistic to use Non-Linear Goal Programming (NLGP) technique [19].

3.2.1.2 Non-Linear Goal Programming Technique

The Goal Programming model is formulated for a given multiple objective problem as follows :

The GP formulation requires to set the aspiration levels (i.e. goal values) for each of the objective function to convert them into goals (i.e. objective goals) in addition to treating all the constraints as absolute (or rigid) goals. The NLGP technique solves to achieve all these goals in the order of the priorities assigned to them. The achievement of a goal is the value by which the function value deviates from its aspiration level. The deviation can be zero deviation, positive deviation (called over achievement) or negative deviation (called under achievement). The optimization of a multiple objective problem is, therefore, converted as a minimization of the achievements in the order of their priorities. The absolute goals are treated as top priority goals and are assigned to the first achievement function. The deviation of this achievement should invariably be zero. Otherwise, no solution exists for the problem.

During the solution procedure, the optimized achievement function value of the previous priority should be treated as the constraint to be satisfied while minimizing the achievement function of the successive lower priority goals. This function. The final solution thus obtained becomes the optimum solution to the multiple objective problem.

The nonlinear goal programming model is expressed in the following manner :

To find $X = (x_1, x_2, \ldots, x_r)$

so as to

$$\min.\ A = [\ a_1(n,p),\ a_2(n,p),\ \ldots\ ,\ a_t(n,p)\ ] \qquad (3.7)$$

subject to

$$g_i\ (x) + n_i - p_i = c_i \qquad i=1,2,\ldots,\ m \qquad (3.8)$$

$$f_j\ (x) + n_{m+j} - p_{m+j} = b_j \qquad j=1,2,\ldots,\ k \qquad (3.9)$$

$$x,\ n_i,\ p_i >= 0 \quad \text{and}\ p_i . n_i = 0 \qquad i=1,2,\ldots,\ m+k$$

Each of the deviation variables is determined from the corresponding equation as follows :

$$n_i = \begin{cases} n_i & \text{if } n_i >= 0 \\ 0 & \text{if } n_i < 0 \end{cases} \qquad (3.10)$$

where $n_i = c_i - g_i\ (x)$ or $n_i = b_i - f_i\ (x)$

Similarly,

$$p_i = \begin{cases} p_i & \text{if } p_i >= 0 \\ = 0 & \text{if } p_i < 0 \end{cases} \qquad (3.11)$$

where $p_i = g_i\ (x) - c_i$ or $p_i = f_i\ (x) - b_i$

The NLGP technique can use any of the sequential search techniques to minimize the achievement function using an iterative approach. In the present work, an improved version of Hookes and Jeeves search technique is employed. The original Hookes and Jeeves method is a search technique consisting of two kinds of moves, one called an exploratory move and the other called the pattern move. An improvement in the exploratory move and Tewari [19] is used in this thesis. In this technique if the exploratory move fails along both the directions for each of the variables, then the exploratory move proceeds along the rotated axes by considering the simultaneous step moves in any two or more variables. This facilitates the search to proceed further without being halted at any of the constrained boundaries . The pattern search proceeds as usual.

The step wise procedure of the NLGP algorithm is depicted in the flow chart shown in Figure 3.1 and is described below .

1. The NLGP model is formulated as discussed. Then the objective function of the NLGP becomes

$$\text{minimize } A = [\ a_1,\ a_2,\ \ldots\ a_t\ ]$$

2. Select the starting base point. The starting base point may be any arbitrary point for minimization of the first achievement. But for the subsequent achievements, the starting base is to be the best point of the previous achievement. The step sizes, dx_j, are taken for corresponding independent variables x_j, $j=1,2,\ldots k$.

3. Make the exploratory move in the positive direction of each of the independent variables. Check whether the move is a success or failure. The move is treated as a success if the value of the current achievement (a_i) at the point considered decreases without violating the previously attained achievement function (i.e., $a_k <= a_k^*$, $k=1,2,\ldots i-1$, with a_k^* being the best achievement attained thus far). If the move is a success, the new point is retained and the procedure is continued with the remaining variables. If the move is a failure in the positive direction of any of the variables, it returns to the previous

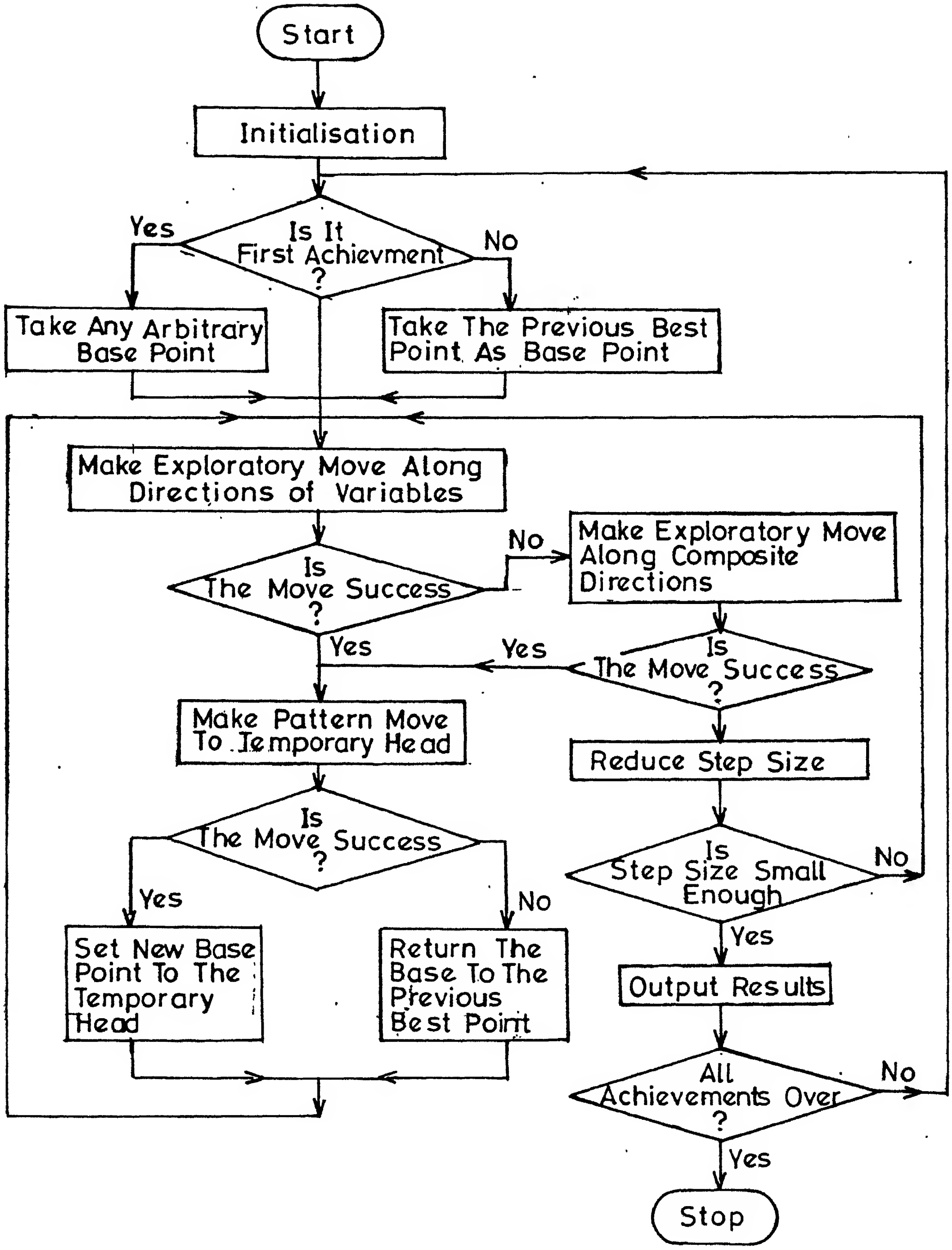

FIG. 3·1 FLOW CHART SHOWING NLGP ALGORITHM the exploratory move is completed for all the variables. If there is at least a single success in the exploratory move, go to step 5, otherwise, go to step 4.

4. Now the exploratory move is carried along the rotated axes (i.e., composite directions). The move along this axis is obtained by considering the step sizes simultaneously for two or more variables. The various combinations of step sizes are tried for success of the move. If there is at least a single success, proceed to step 5, otherwise, go to step 6.

5. Make the pattern move to locate the temporary head (X) using the previous base points.

$$X = X_B + \alpha(X_B - X_B') \quad (3.12)$$

where,

X_B is the best point from which the pattern move is considered .

X_B' is either the starting base point or the preceding base point and

α is the acceleration factor.

If the move is success, go to step 3. If it is a failure, the base point is returned to the previous point X_B . Go to step 3.

6. If the step size becomes less than a specified small value, (epsilon) go to step 7, otherwise, reduce the step size and go to step 3.

7. Set the optimum value of the current achievement as a_i^*. If all the achievements are exhausted, proceed to step 8, otherwise, go to step 2.

3.2.1.3 Some Difficulties Associated With GP

While GP offers a great deal of flexibility in solving problems, there are a number of nagging difficulties associated with its use. One such difficulty is the manner in which the pre-emptive priority structure is chosen and the effect this ordering has upon the solution produced. Even though considerable care is exercised in developing this priority structure, there may still be uncertainty regarding the assignment of priority levels in a manner that actually reflects the objectives of the Decision Maker. While the effect of reordering these priorities can be investigated by all such permutations of priority structures, this would be highly inefficient. Moreover it would typically produce a large number of solutions, many of which would be highly similar and overlapping in nature. Therefore, in order to ensure correct or even rational solutions to the GP model, changes in priority assignments have to be investigated in a logical, efficient manner.

A second difficulty typically associated with GP is determining proper values for the target level goals.

3.2.2 The NLGP Model of EDM

The physical constraints on the decision variables are expressed as the constraints. Thus, if D_{min} and D_{max} represent the limits on the tool diameter, then the tool diameter constraint is represented as

$$D_{min} <= D <= D_{max} \qquad (3.13)$$

Similarly, physical constraints on the other parameters

The physical constraint on depth of penetration

$$d_{min} <= d <= d_{max} \qquad (3.14)$$

The physical constraint on ontime

$$t_{min} <= t <= t_{max} \qquad (3.15)$$

Hence, the problem is to determine the optimum values of tool diameter, depth of penetration and ontime so as to achieve as far as possible the following goals :

1) the MRR goal, i.e., the MRR given by the expression (3.1) must be greater than or equal to a specified value (for maximization).

2) the SR goal, i.e., the surface roughness value given by the expression (3.2) is to be lesser than or equal to a specified value (for minimization).

3) the OC goal, i.e., the overcut on the machined work piece given by the equation (3.3) should be less than or equal to a specified value.

4) the REW goal, i.e., the REW obtained from equation (3.4) should be less than or equal to a specified value.

5) the TWR goal, i.e., the rate of wear of the tool electrode should be less than or equal to a minimum value.

6) the TPR goal seeks to minimize the taper on the finished work piece. This takes the form that the taper given by the equation (3.6) should be less than or equal to a specified value.

7) the tool diameter goal, i.e., the tool diameter should be within the limits defined by equation (3.13)

8) the depth of penetration goal seeks to satisfy the constraint described by the equation (3.14).

) the ontime goal , i.e., the ontime value should be within the bounds imposed as described in equation (3.15).

Since the goals (7), (8), (9) are limitations on the machine, they are to be treated as absolute (or rigid) goals and should be given first priority.

A distinguishing feature of this formulation is that we can define a number of objective functions for equation (3.7) each representing a particular priority assignment.

CHAPTER 4

IMPLEMENTATION

The mathematical modeling of the EDM process in the previous chapter leads to a simplification of the model of the process without losing the accuracy of the description . This chapter describes the implementation of the system developed to solve problems of the type discussed in the previous chapter.

4.1 System Description

A computer program based on the approach described in this work makes it possible to determine the optimal machining conditions.

The current computer implementation of the decision analysis is based on a two stage model of the decision making process. In the first stage - the input stage - the decision maker is required to enter the various run parameters viz., step size, stopping criteria, starting points, the goal values, etc. In the second stage - the search stage - the decision maker uses the system in an interactive way to analyze the possible efficient alternatives guided by his reference objectives (goal values).

The initial information for the input stage, specifically the initial starting point, is provided by minimizing all of the objectives separately. A matrix D_s which yields information on the range of numerical values of each objective is then constructed. This matrix called the decision support matrix [7] would give the decision maker an overview of

$$D_s = \begin{bmatrix} q_1 & q_2 & \ldots & q_i & \ldots & q_p \\ q_1^2 & q_2^* & \ldots & q_i^2 & \ldots & q_p^2 \\ \vdots & \vdots & & \vdots & & \vdots \\ q_1^j & q_2^j & \ldots & q_i^* & \ldots & q_p^j \\ \vdots & \vdots & & \vdots & & \vdots \\ q_1^p & q_2^p & \ldots & q_i^p & \ldots & q_p^* \end{bmatrix}$$

In the matrix D_s row j corresponds to the solution vector x_j which minimizes objective q_j. The vector with elements $q_i^1 = q_i^*$,i.e., the diagonal of D_s represents the "utopia" or the ideal point. This point is not attainable (if it were, it would be the solution of the proposed decision problem), but it may be presented to the decision maker as a guideline to construct the initial starting point and the goal values.

The general structure of the system is presented in Figure 4.1. The user may input his objective functions through an interactive "editor" . This provides for a way to manipulate through a series of terms, such that the final function form is obtained. The program can, then, draw input from an existing file or from the user through the keyboard and automatically compile, link, prepare the decision matrix and initiate the optimization process.

The search of the decision analysis is supported by a computer program developed on the basis of the algorithm described in chapter 3.

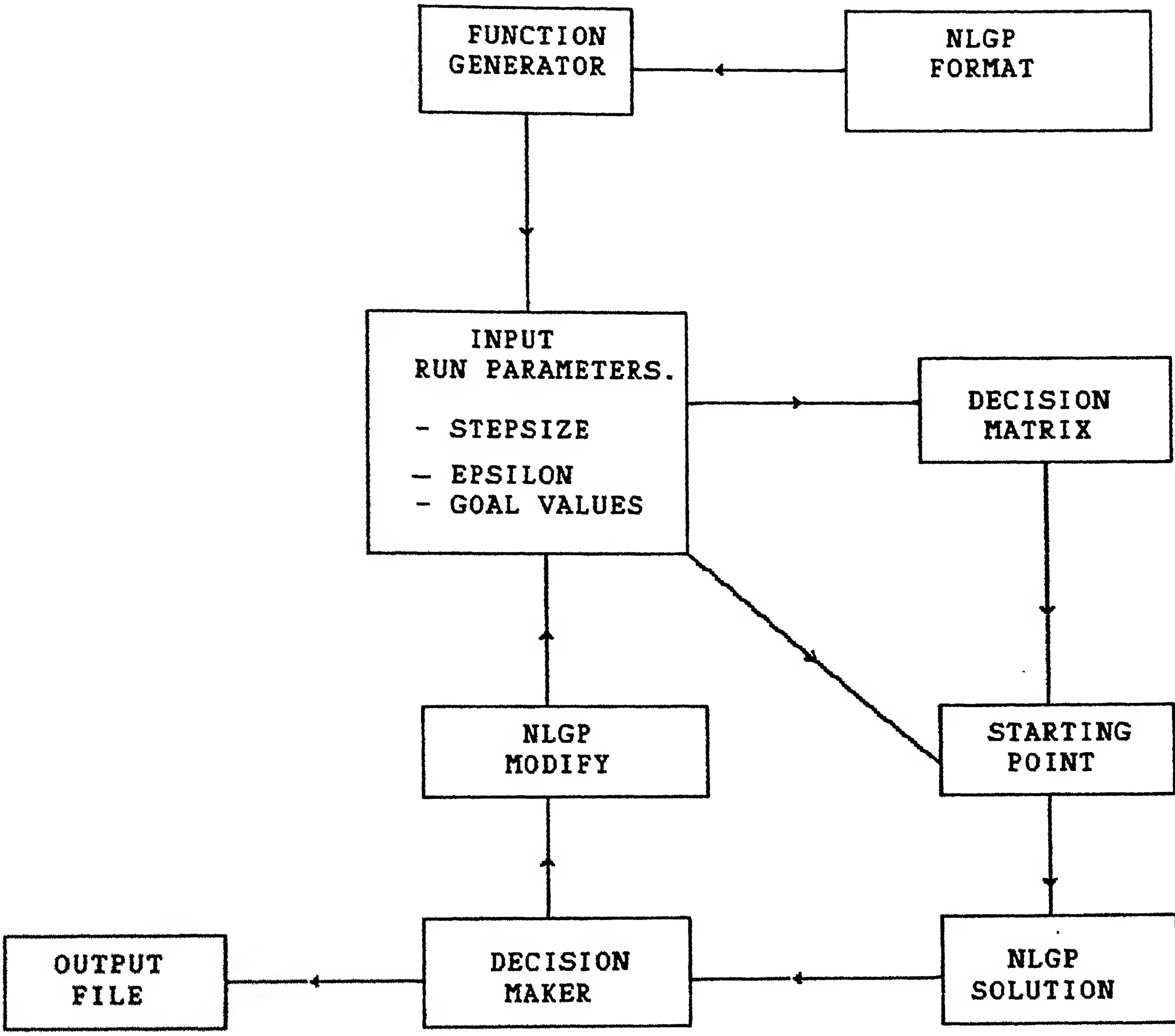

Fig 4.1 : System Structure

After each run, the decision maker can modify the goal values, or rotate the priority assignments of the objective functions or change the other run parameters so as to obtain a solution which is best in tune with his stated goals.

The system also provides for a way of storing the solutions generated in each run onto a file so that the decision maker can chose later from this set of "goal efficient" solutions.

The distinguishing features of the system are :

- the interactive "function generator"
- the preprocessor, which converts the objective functions into standard turbo pascal format
- the optimization module, which extracts information from the system and attempts to optimize the problem
- the postprocessor, which displays the necessary information to the decision maker on the screen, and later, to a file if necessary.

CHAPTER 5

RESULTS AND DISCUSSION

In the preceding chapters, the problem of determinin the optimal parameters for EDM has been structured as an NLG model. In this chapter, we illustrate a few applications of suc an approach by considering a few examples.

5.1 Numerical Examples

Two examples are considered in this section. The firs one solves the model developed in Chapter 3 and the second on deals with the problem investigated by Mukherjee and Pal [13].

5.1.1 Example 1

Consider a case where the objective functions to b optimized are MRR, OC, SR, REW, TWR and TPR. The relationship o these objectives to the parameters viz., tool diameter, depth o penetration and ontime are estimated and given by equations (3.1 to (3.6). Let the goals on the various objectives be fixed a follows :

MRR = 25 mg/min

OC = 0.07 mm

SR = 2.5 microns

REW = 15 %

TWR = 5 mg/min

TPR = 2 deg.

Let the initial priorities be in the same order as given.

The bounds on the variables are taken as follows :

Variable	L. bound	U. bound	
D	9	13	mm
d	4	16	mm
t	10	200	u secs

Then the mathematical model of the above process becomes a follows ;

$$MRR = 34.5359\ D^{0.410}\ d^{-0.014}\ t^{0.435}\ e^{0.007t} \quad >= 25 \qquad (5.1$$

$$OC = 0.0159\ D^{0.524}\ d^{-0.031}\ t^{0.020}\ e^{0.002t} \quad <= 0.07 \qquad (5.2$$

$$SR = 1.15027\ D^{-0.088}\ d^{0.031}\ t^{0.283}\ e^{0.001t} \quad <= 2.5 \qquad (5.3$$

$$REW = 4225.95\ D^{-0.901}\ d^{-0.014}\ t^{-1.099}\ e^{0.007t} \quad <= 15 \qquad (5.4$$

$$TWR = 641.62\ D^{-0.085}\ d^{-0.164}\ t^{-1.499}\ e^{0.014t} \quad <= 5 \qquad (5.5$$

$$TPR = -0.124 + 1.539/D + 7.441/d + 7.502/t \quad <= 2 \qquad (5.6$$

subject to

$$9 <= D <= 13 \qquad (5.7$$

$$4 <= d <= 16 \qquad (5.8$$

$$10 <= t <= 200 \qquad (5.9$$

The goal programming format becomes

$$D + n_1 - p_1 = 9 \qquad (5.10$$

$$D + n_2 - p_2 = 13 \qquad (5.11$$

$$d + n_3 - p_3 = 4 \qquad (5.12$$

$$d + n_4 - p_4 = 16 \qquad (5.13$$

$$t + n_5 - p_5 = 10 \qquad (5.14$$

$$t + n_6 - p_6 = 200 \qquad (5.15$$

Equations (5.10) to (5.15) represent the absolute goals or th

rigid goals.

The objective goals are :

$$MRR + n_7 - p_7 = 25 \quad (5.16)$$

$$OC + n_8 - p_8 = 0.07 \quad (5.17)$$

$$SR + n_9 - p_9 = 2.5 \quad (5.18)$$

$$REW + n_{10} - p_{10} = 15 \quad (5.19)$$

$$TWR + n_{11} - p_{11} = 5 \quad (5.20)$$

$$TPR + n_{12} - p_{12} = 2 \quad (5.21)$$

The achievements functions as per the original priorities are :

$a_1 = n_1 + p_2 + n_3 + p_4 + n_5 + p_6$ (for the rigid goals)

$a_2 = p_7$ (for MRR)

$a_3 = p_8$ (for OC)

$a_4 = p_9$ (for SR)

$a_5 = p_{10}$ (for REW)

$a_6 = p_{11}$ (for TWR)

$a_7 = p_{12}$ (for TPR)

The achievement function vector, A_1, for the problem with the above priority assignments is given by

$$A_1 = [\ a_1, a_2, a_3, a_4, a_5, a_6, a_7\ ]$$

5.1.2 Results and Discussion

Table 5.1 gives the results for the single objective optimization. The single objective optimization solution is different for some of the objectives. This indicates that the problem is characterised by conflicting objectives. Thus, the decision maker has to choose a compromise solution. These results may be presented to the decision maker in the form of a decision matrix to help set a priority structure and fix the target values. The decision matrix is identified in Table 5.1.

Throughout the analysis, functions which are to be maximized are converted to minimization by taking the negative of the original function. For example, MRR which is to be maximized is treated as (-MRR) since minimization of (-MRR) is equivalent to maximization of MRR.

5.1.2.1 Three Variable Case

The optimum solution for the three variable case is shown in Table 5.2. This optimum achievement implies that all the constraints (rigid goals) and the objective goals have been satisfied.

A number of other formulations can also be considered so as to reflect the attitude of the decision maker. Each formulation is obtained by rotating the priority assignments of he various objective functions. For example, by interchanging priorities of the objectives, we get a new achievement vector given by

$$A_2 = [a_1, a_2, a_5, a_4, a_7, a_6, a_3].$$

The results of such different priority assignments are given in Table 5.2. In the second formulation, where TPR is given a higher priority, it is observed that there is a significant improvement in its achievement. This improvement is, however, achieved only at the expense of OC. REW and TWR are also significantly changed - although favorably.

OC is given a higher priority, ahead of SR, in the third formulation, while the priorities for the rest of the objectives are undisturbed. This results in only a slight improvement in its value. In the fourth formulation, it is found that a high priority for SR does not seem to improve its achievement. Instead, TPR is improved significantly.

Thus, it can be seen that the NLGP model for the EDM provides solutions with due considerations of the target values and the priority structure as specified by the decision maker.

5.1.2.2 Two Variable Case

The proposed problem is also solved for a two variable case, i.e., one of the three parameters is fixed at a particular value with the other two permitted to vary. Goal values for the functions and the priorities are kept unchanged. The results are presented in Tables 5.3, 5.4 and 5.5.

When the tool diameter is kept constant and depth of penetration and ontime are allowed to vary, it is observed that the goal requirements are satisfied only when the diameter is greater than 9 mm. From Table 5.3, we can observe that at D=9, the REW has to be relaxed so that the goals can be achieved.

When the depth of penetration is fixed, and tool is limited to values of d which are less than 8 mm. Table 5.4 summarizes the results.

By allowing the tool diameter and depth of penetration to vary and by fixing the ontime at a constant value, it is observed that there is no feasible region at all. This implies that in order to achieve feasibility, it is essential that ontime be allowed to vary. Summary of the results for this case are presented in Table 5.5.

5.1.3 Example 2

Based on results reported [16] with H.S.S work material and copper tool in kerosene medium, the following relationships are estimated for an RC - based Electro Discharge Machining process.

$$MRR = 24\ R^{-4.00}\ C^{5.5} \qquad (5.22)$$

$$EWR = 45\ R^{-3.00}\ C^{4.00} \qquad (5.23)$$

$$EWR/MRR = 1.887\ R\ C^{-1.5} \qquad (5.24)$$

$$\tan x = 0.235\ C^{0.003} \qquad (5.25)$$

$$H = 4\ C^{0.28} \qquad (5.26)$$

where x = taper angle (degrees)

H = maximum height of surface roughness (microns)

EWR = Electrode Wear Rate

The problem now is to determine the optimal parameters (R and C) such that the following goals are achieved :

1. taper goal, i.e., the taper expressed by eqn. (5.25) should be less than or equal to a specified value - assumed to be 0.268 (tan(15)) - in this case.

value should be less than or equal to 10 microns

3. the MRR goal, set at 4000 ugms /sec
4. the EWR goal, set at 1400 ugms /sec
5. the REW goal, set at 0.5

The minimum values for resistance and capacitance are assumed to be 25 ohms and 1 uF respectively.

Then the mathematical model becomes as follows :

$$TPR = 0.235\ C^{0.003} \tag{5.27}$$

$$SR = 4\ C^{0.28} \tag{5.28}$$

$$MRR = 24\ R^{-4.00}\ C^{5.5} \tag{5.29}$$

$$EWR = 45\ R^{-3.00}\ C^{4.00} \tag{5.30}$$

$$REW = 1.887\ R\ C^{-1.5} \tag{5.31}$$

subject to

$$R >= 25 \tag{5.32}$$

$$C >= 1 \tag{5.33}$$

Since goals (5.32) and (5.33) are the process and design limitations, they are to be treated as absolute goals and hence are given first priority. Also, since taper and surface roughness are treated as constraints in the original problem, they are given the second and third priorities respectively.

The final NLGP model of the problem is as follows :

$$R + n_1 - p_1 = 25 \tag{5.34}$$

$$C + n_2 - p_2 = 1 \tag{5.35}$$

$$TPR + n_3 - p_3 = 0.286 \tag{5.36}$$

$$SR + n_4 - p_4 = 10 \tag{5.37}$$

$$MRR + n_5 - p_5 = 4000 \tag{5.38}$$

$$EWR + n_6 + p_6 = 1400 \tag{5.39}$$

$$REW + n_7 + p_7 = 0.5 \tag{5.40}$$

The achievement functions as per the priorities are

$$a_1 = n_1 + n_2$$

$$a_2 = p_3$$

$$a_3 = p_4$$

$$a_4 = p_5$$

$$a_5 = p_6$$

$$a_6 = p_7$$

and the achievement vector is

$$A = [\ a_1,\ a_2,\ a_3,\ a_4,\ a_5,\ a_6\ ]$$

Taking the starting point as $R = 25$ and $C = 1$ the solution obtained is

$$R^* = 25$$

$$C^* = 26.37$$

These optimum values are in agreement with the results obtained by Mukherjee and Pal [13].

A new optimal solution has been obtained by assigning REW a higher priority than EWR (Table 5.6) This solution vector has not been reported by Mukherjee and Pal since in their model, there is no way of incorporating the decision maker's preferences with the solution set obtained previously shows that the first set has better values for all the objectives except surface roughness and to a very small extent, taper. Indeed, if surface roughness and taper also had been better, the second solution though "goal efficient" would have been "dominated" by the first set. This shows that the assigning of priorities, though subjective, is essential for a successful exploitation of the process.

TABLE 5.1 : Single Objective Optimization

Problem Formulation	Objective function values						Solution Set		
	-MRR	OC	SR	REW	TWR	TPR	D	d	t
Min (-MRR)	-38.4764	0.0933	3.6630	4.8371	1.9138	0.4970 *	13	16	200
Min (OC)	-32.8460	0.0517	1.8800	48.8792	15.4608	2.6574	9	4	10
Min (SR)	-32.8460	0.0517	1.8800	48.8792	15.4608	2.6574	9	4	10
Min (REW)	-38.4764	0.0933	3.6630	4.8371	1.9138	0.4970	13	16	200
Min (TWR)	-28.0370	0.0803	3.4306	4.8157	1.4202	0.6745	13	12	125
Min (TPR)	-38.4764	0.0933	3.6630	4.8371	1.9138	0.4970	13	16	200

* identifies the decision matrix

TABLE 5.2 : RESULTS FOR DIFFERENT PRIORITIES.

	Objective Functions						Solution Set		
	MRR mg/min	OC mm	SR um	REW %	TWR mg/min	TPR deg.	Tool Dia. mm	Depth of pen. mm	Ontime us
Target	-25.00	0.07	2.5	15.0	5.0	3.0			
Priorities	1	2	3	4	5	6			
Objective fn. Values	-25.4293	0.0599	2.4759	14.6452	3.8139	1.5450	10.875	5.875	28.75
Priorities	1	4	3	6	5	2			
Objective fn. values	-26.9773	0.0653	2.4875	11.9526	3.4095	1.1746	13.0	8.0	30.0
Priorities	1	3	4	6	5	2			
Objective fn. values	-27.1618	0.0647	2.4769	12.3793	3.4498	1.0088	13.0	9.0	28.75
Priorities	1	4	2	6	5	3			
Objective fn. values	-27.0685	0.0642	2.4959	12.3368	3.3136	0.8747	13.0	12.625	28.75

TABLE 5.3 : RESULTS FOR TWO VARIABLE CASE FOR CHANGE IN D .

Const. D mm	Optimal d mm	Optimal t us	Objective Functions -MRR mg/min	OC mm	SR um	REW %	TWR mg/min	TPR deg.	All Goals achieved?
Target			-25.00	0.07	2.5	15.0	5.0	3.0	
9	5.25	22.5	-25.08	0.054	2.36	21.80	5.22	1.80	NO
11	5.875	28.75	-25.55	0.060	2.4	14.50	3.81	1.54	YES
13	7.0	30.0	-27.03	0.066	2.48	11.98	3.49	1.31	YES

TABLE 5.4 : RESULTS FOR TWO VARIABLE CASE FOR CHANGE IN d .

	Optimal		Objective Functions						
Const. d mm	D mm	t us	-MRR mg/min	OC mm	SR um	REW %	TWR mg/min	TPR deg.	All Goals achieved?
Target			-25.00	0.07	2.5	15.0	5.0	3.0	
4	12.25	32.5	-26.13	0.065	2.50	11.87	3.53	2.10	YES
8	10.875	28.75	-25.32	0.059	2.50	14.58	3.63	1.21	YES
12	10.625	26.25	-25.49	0.058	2.48	16.08	3.76	0.93	NO
16	10.50	25.0	-25.59	0.056	2.47	16.93	3.80	0.79	NO

TABLE 5.5 : RESULTS FOR TWO VARIABLE CASE FOR CHANGE IN t .

Const. t us	Optimal D mm	Optimal d mm	Objective Functions -MRR mg/min	Objective Functions OC mm	Objective Functions SR um	Objective Functions REW %	Objective Functions TWR mg/min	Objective Functions TPR deg.	All Goals achieved?
Target			-25.00	0.07	2.5	15.0	5.0	3.0	
10	9	4	-32.85	0.052	1.88	48.88	15.46	2.66	NO
50	9	4	-21.58	0.058	2.85	11.03	2.42	2.06	NO
100	9	4	-22.65	0.065	3.30	7.31	1.73	1.98	NO
150	9	4	-26.95	0.072	3.52	6.64	1.89	1.96	NO
200	9	4	-33.74	0.080	3.63	6.57	2.48	1.95	NO

TABLE 5.6 : RESULTS FOR EXAMPLE 2

	Objective functions					Starting Point		Solution set	
	TPR deg.	SR um	-MRR mg/min	EWR mg/min	REW	R ohms	C uF	R ohms	C uF
Target Values	0.268	10.000	-4000	1400	0.5				
Priorities	1	2	3	4	5				
Objective fn. values	0.237	9.998	-4014.16	1390.38	0.349	25.00	1.00	25.00	26.36
Target values	0.268	10.000	-1000	510	0.5				
Priorities	1	2	3	5	4				
Objective fn. values	0.237	9.589	-1022.83	508.04	0.499	25.00	1.00	28.66	22.70
Target values	0.268	10.000	-1000	500	0.5				
Priorities	1	2	3	5	4				
Objective fn. values	0.237	9.734	-1004.90	497.93	0.499	35.00	26.37	31.03	23.98

CHAPTER 6

CONCLUSIONS AND SCOPE FOR FUTURE WORK

6.1 Conclusions

The following conclusions can be drawn from the present study :

1. The problem of determination of optimal parameters for EDM satisfying many objectives can be structured as a standard Non-Linear Goal Programming problem.

2. The method described in this work provides for a decision making mechanism which is in tune with the statéd goals of the decision maker as well as within the operational and design constraints. It also allows the decision maker to view the effect of varying the targets of the goals and its priorities.

3. Wider flexibility (in terms of alternate "optimal" solutions) is available for the solution of the multi-objective problem when all the three variables , viz., tool diameter, depth of penetration and ontime are considered simaltenously.

4. In a two variable case, depth of penetration offers the maximum flexibility, followed by tool diameter. Ontime offers the least flexibility.

5. The results obtained with the present NLGP technique for Example 2 (Chapter 5) are same as those obtained by Mukherjee and Pal [13].

6. The method described in this work enables one to determine

combinations of working parameters. For example, the maximum obtainable MRR for a particular set of REW - SR combination can be determined.

6.2 Scope For Future Work

1. Further work can concentrate on determining the optimal machining conditions for workpieces of complicated shapes and for different types of electrodes and workpiece materials.

2. In the present method, the optimum solution is influenced by the selection of the starting points and stepsizes. This necessitates carrying out a large number of trials to arrive at the "best" solution. A suitable methodology can be developed to overcome this drawback.

3. A "technological surface" can be developed for an EDM system (A "technological surface" is a graphical or mathematical representation of the border limits of performance of an EDM system in terms of MRR, REW and SR , or any other evaluatio criteria). Such "technological surfaces" offer a way o evaluating the merits and demerits of a particular EDM system.

To determine just one point of the technologica surface, the maximum obtainable MRR has to be determined from on set of REW-SR combination. This reduces to an optimizatio problem for finding the best set of working parameters yeildin the maximum MRR.

APPENDIX A

Model developed by Indurkhya:

Ontime, Tool Diameter, and Depth of Penetration were considered as controllable variables to study the effect of each of them on Material Removal Rate, overcut, taper, surface roughness, Relative Electrode Wear and Tool Wear Rate. The experiments were conducted on ELEKTRA EMS 4025 machine. The parameters such as open voltage, working voltage, discharge current, duty factor and flushing pressure were kept unchanged. The experiments were performed according to the design of experiments.

A polynomial response surface equation of second order can be represented as

$$Y_u = B_0 + \text{SUM } B_i X_i + \text{SUM } B_{ii} X_i^2 + \text{SUM } B_{ij} X_i X_j$$

where Y_u is the response (i.e., MRR, TWR, REW, etc.) and

X_i = 1,2, ... K are the coded levels of K quantitative variables or factors (i.e., t, D, d). The coeffiecients B_0, B_1, etc. are known as regression coefficients . The polynomial is also known as the Regression Function.

The actual values of the coded levels for the factors X_1 (Tool Diameter, D), X_2 (Depth of penetration , d) and X_3 (Ontime , t) are shown in Table A.

Based on the above postulated second order in coded levels, mathematical models in terms of the actual design values of each variable were obtained by transformation and multiple regression.

Table A : Values of Levels for different Factors :

Factors	Symbol	Levels				
		-2	-1	0	1	2
Diameter (mm)	X1	9	10	11	12	13
Depth (mm)	X2	4	7	10	13	16
Ontime	X3	10	20	50	100	200

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